A COLLECTIVE-COMPUTATION APPROACH TO PROGNOSTICS HEALTH MANAGEMENT

PIs: Huan Liu, Aditi Chattopadhyay
Antonia Papandreou-Suppappola

Graduate Students: G. Varadarajan
Y. Liu, J. Zhang

Research supported by NASA IVHM Program
Grant NNX08AY51A, Technical Monitor: Edward Balaban

NASA Aviation Safety Technical Conference
Denver, Colorado
October 21-23, 2008

IVHM and Prognosis

MOTIVATION

- **Prognosis metrics that emphasize statistical & mathematical rigor and validation strategies**
- **Selection of data sources with relevant features**
- **Robust damage prediction methodologies integrating physics-based and data-driven models**
- **Validation of new prognosis metrics on focus problem**

STATE-OF-THE-ART

Existing non-IVHM based prognosis approach

1. Safe-life Approach
Metric: statistical total life

2. Fail-life Approach
Metric: statistical total life

3.Miner-ruler based linear damage Accumulation life estimation
Metric: miner ratio

Linear fracture mechanics based Damage-tolerant approach

4. Paris type Model with no closer effect
Metric: critical Stress intensity or crack length

5. Newman type Model with load Sequence and closer Effect
Metric: critical stress Intensity or crack length

Novel Metrics

Current IVHM based prognosis approach

6. Stochastic Crack growth model
Metric: stochastic crack length

7. Improved Miner rule with nonlinear stochastic damage accumulation life estimate
Metric: stochastic total life

Existing IVHM based prognosis approach

8. Data mining based precursory signal to damage

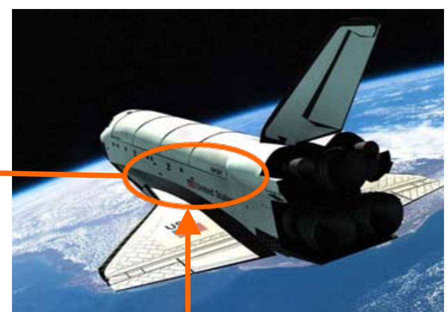
9. Integrated prognostic bearings reasoner for bearing failure prognosis
Metric: Information Smoothing, Fading

PROJECT OBJECTIVES

Examine evaluation metrics & develop a novel prognostic framework using collective-computation approaches combined with data-driven models and physics-based models.

Evaluate extant prognostic metrics & design new metric for evaluation consistency

Integrate/reduce data from multiple sources; complementary feature selection & compressive sensing



Develop robust prognostic framework using data-driven & physics-based models

Integrated Vehicle Health Management

States acquisition & diagnosis

IVHM and Prognosis

RESEARCH TASKS

Task 1: Evaluation of existing prognostic metrics

- **effectiveness to represent uncertainties from noise, imperfect models, future anticipated loads & environmental conditions**
- **mathematical stochastic-based metric for dynamic system; provides bound on minimum possible variance of estimated damage state**

Task 2: Intelligent data selection & reduction

- **smart use of massive, heterogeneous data from multiple sources; employ appropriate data sources with relevant features**

  source selection & feature selection

- **complementary feature selection: remove redundant & irrelevant features**
- **compressive sensing: recover complete data from randomly sampled data & reduce dimensionality & complexity.**

RESEARCH TASKS (CONTD.)

Task 3: Experimentation, Validation & Application

Generate data for hybrid prognosis procedure

Experiments with complex composite sections

Bi-axial/torsion test system

Refine novel algorithms by high performance computing

Validate new prognosis metrics and frameworks

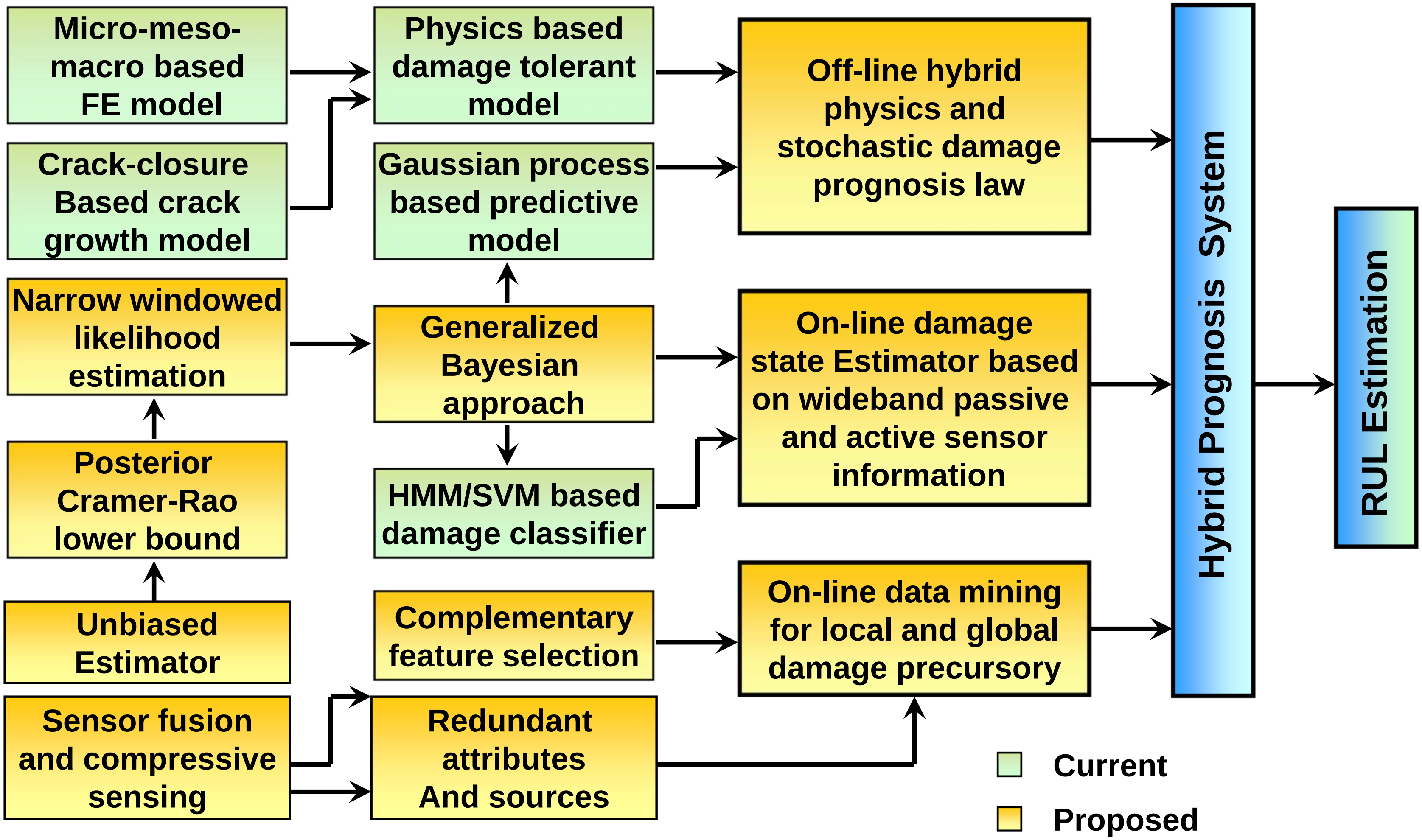
IVHM Milestones Supported

Milestone 3.3.2 *Guidelines for fidelity of prognostic estimates*

Milestone 3.3.3 *Methodology for assessing the performance of prognostic algorithms and methods*

Milestone 3.3.5 *Assessment of the ability to perform prognostic reasoning*

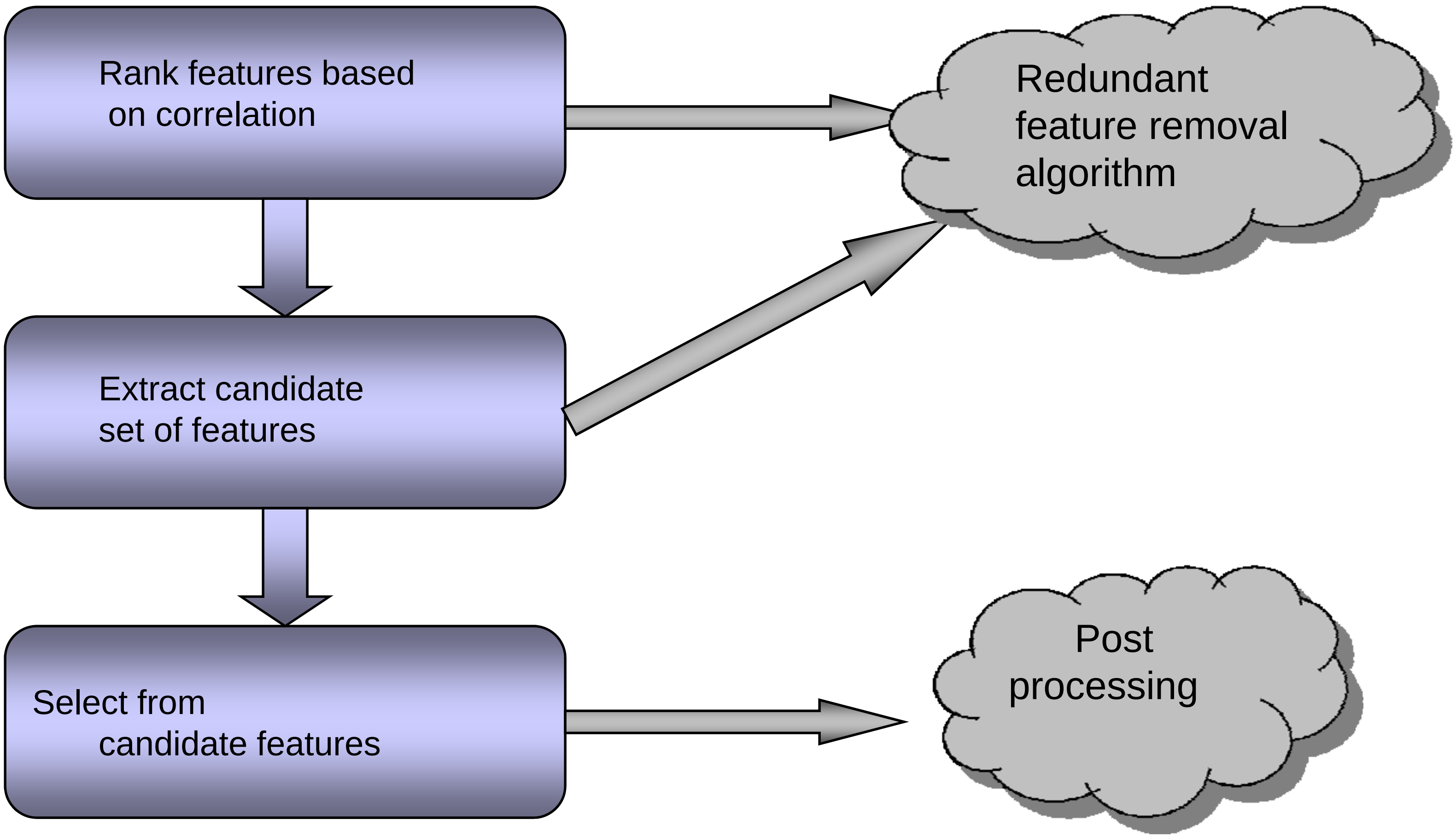
DETAILED ARCHITECTURE



COMPLEMENTARY FEATURE SELECTION

- **2^N search space for *N features; exponential growth in number of* features causes computational & statistical problems (overfitting).**
- **Proposed framework: complementary feature selection to remove redundant & irrelevant features**
  - **Extract features using canonical correlation analysis that utilizes pair-wise samples from two information sources**
  - **Candidate feature selection selects top features from different views; feature relevance is used to rank features in each view**
- **Canonical feature selection algorithm: filter algorithm that uses backward elimination to remove irrelevant & redundant features by removing within-set redundant features; within-set irrelevant features; & cross-set redundant features**

COMPLEMENTARY FEATURE SELECTION



COMPRESSIVE SENSING

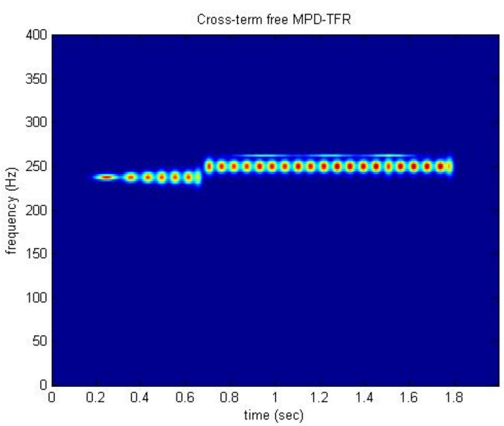
- **High sampling frequencies yield many data samples that require high computational processing cost, & increased transfer & storage space**
- **Many natural signals, *x(t),* have sparse representations: when expanded in terms of basis functions, *x=A s*, (e.g. wavelet, matching pursuit decomposition), most coefficients, *s*, are zero**
- **Find stable measurement matrix B (random) such that y=Bx & a reconstruction algorithm to obtain *x* from only *M* samples of measurement *y.***

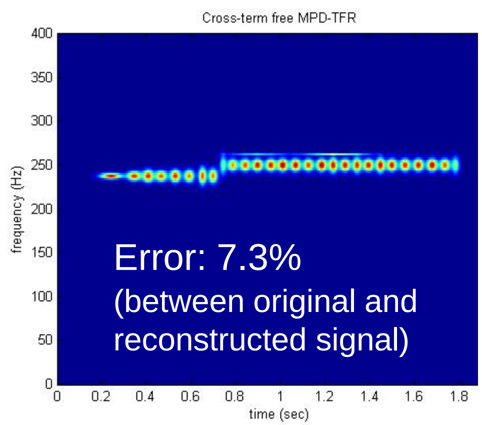
→ **Matrix B is a random matrix**

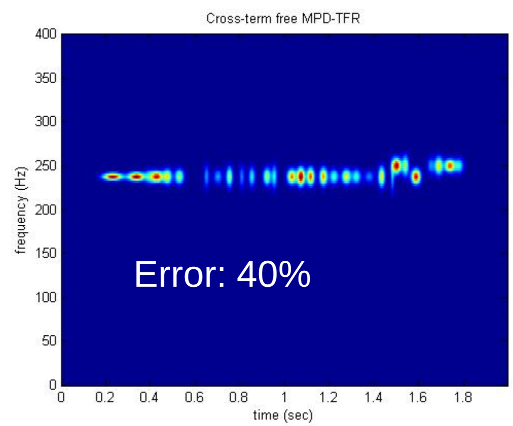
Feature Extraction with Reduced Data Sets

- **Compressed sensing with matching pursuit decomposition (MPD) used to extract important features for prognosis using a reduced data set; preliminary results with milling machine wear data from NASA Ames.** ***: 7.3% error***

A. Agogino and K. Goebel (2007). Mill Data, BEST lab, UC Berkeley. NASA Ames Prognostics Data Repository







MPD time-frequency plots

Conventional sampling

9,000 samples

Random sampling

1,800 samples

Random sampling

900 samples

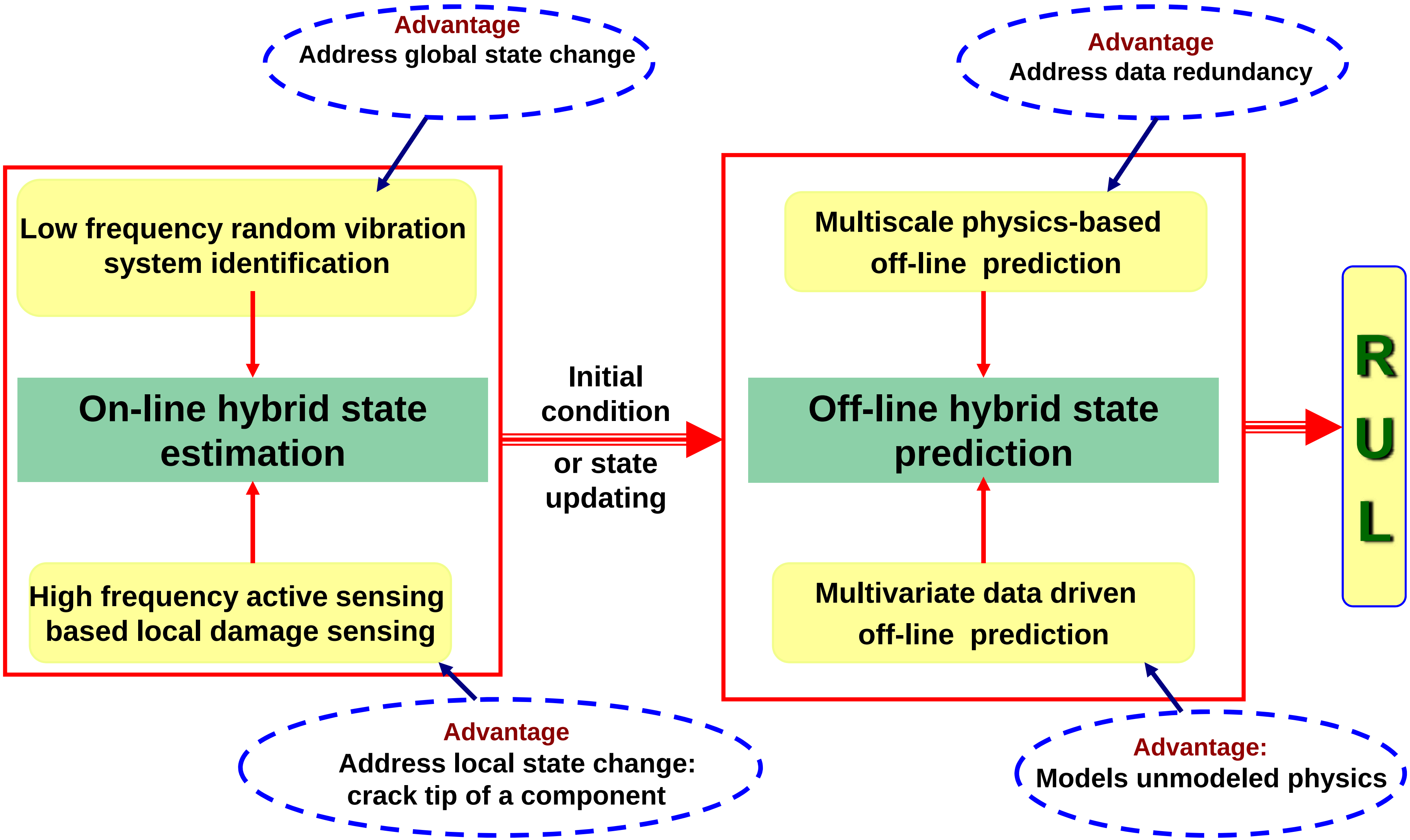
IVHM and Prognosis

ROBUST HYBRID PROGNOSIS

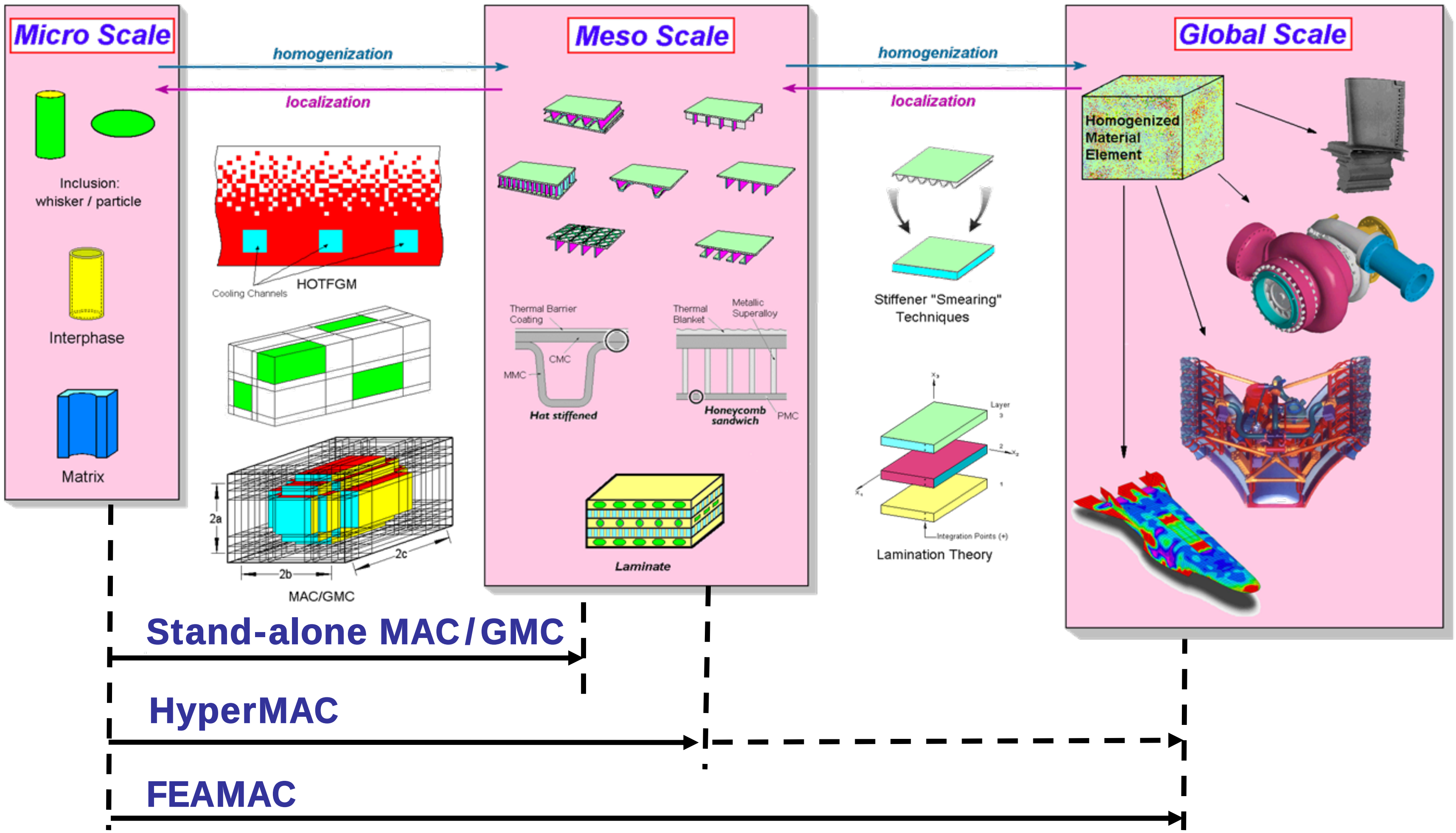
- **Need for physics-based models:**
  - **Manifestations of microscale defects in macroscale phenomena observed experimentally but not adequately explained/modeled**
  - **Fundamental understanding of physical phenomena unique to multiple & coupled damage modes, dynamic response due to complex stress wave patterns, nonlinear energy absorption during impact loading – critical issues associated with heterogeneous material systems**
  - **Virtual sensing to detect very small crack and precursor to damage**
  - **Configuration independent damage interrogation**
  - **Off-line damage prognosis**

Need computationally efficient multiscale models that can bridge the relevant length scales

HYBRID PROGNOSIS ARCHITECTURE



PHYSICS-BASED MULTISCALE MODEL



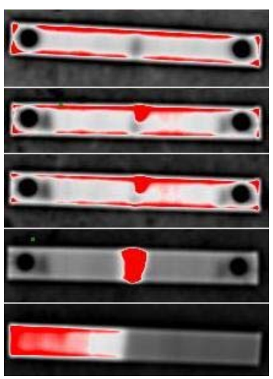
*Courtesy, Dr. Steve Arnold, NASA GRC

COMPOSITE BEAM FATIGUE TEST

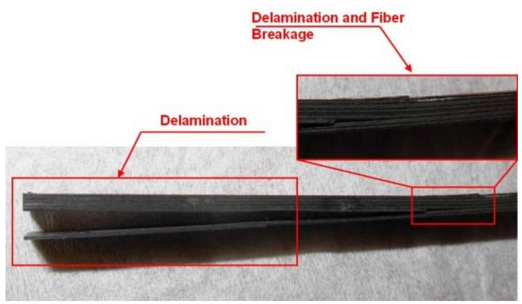
Preliminary results: progressive damage of simple composite structure.

Key Issues:

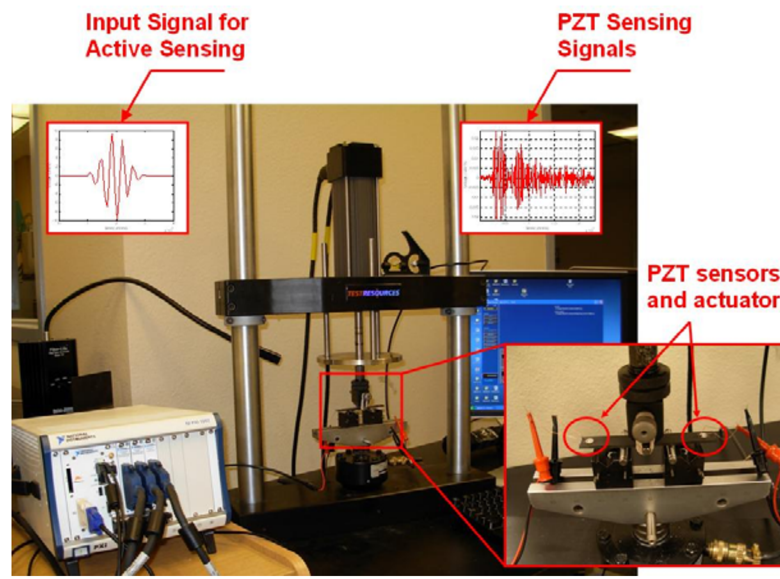
- Active sensing with PZT wafers
- Cyclic loading for progressive damage
- Signal processing & feature extraction with wavelet analysis
- Prognosis with Gaussian process estimation



Progressive damage displayed by Echo Therm

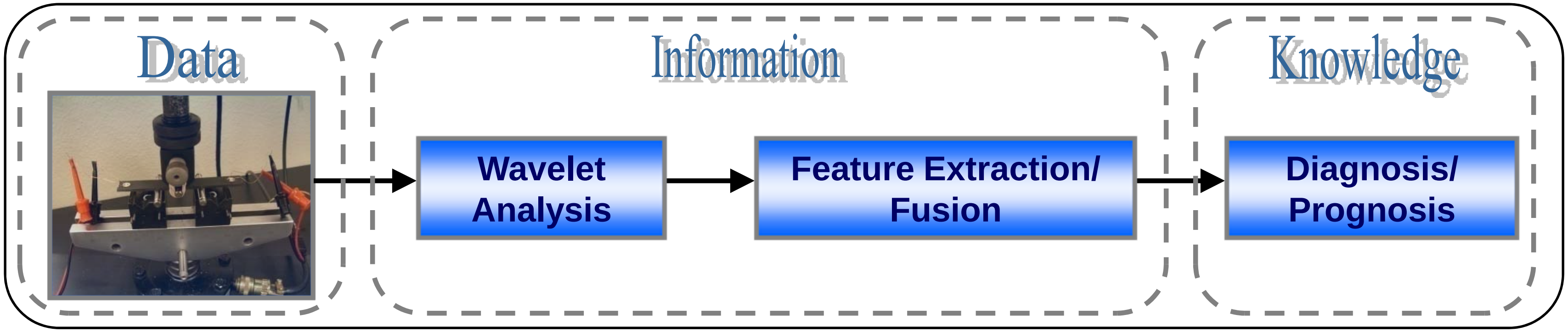


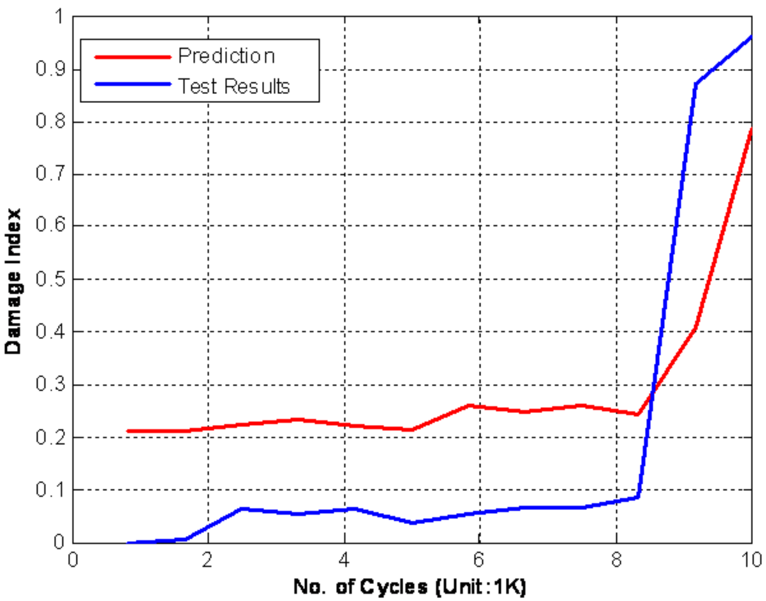
Final failure modes of composite specimens



Experimental setup

GAUSSIAN PROCESS ESTIMATION





Techniques:

➢ "Damage index" indicates wave energy of decomposed sensing signals

➢ Four specimens were tested;
five to ten states were recorded in each test;

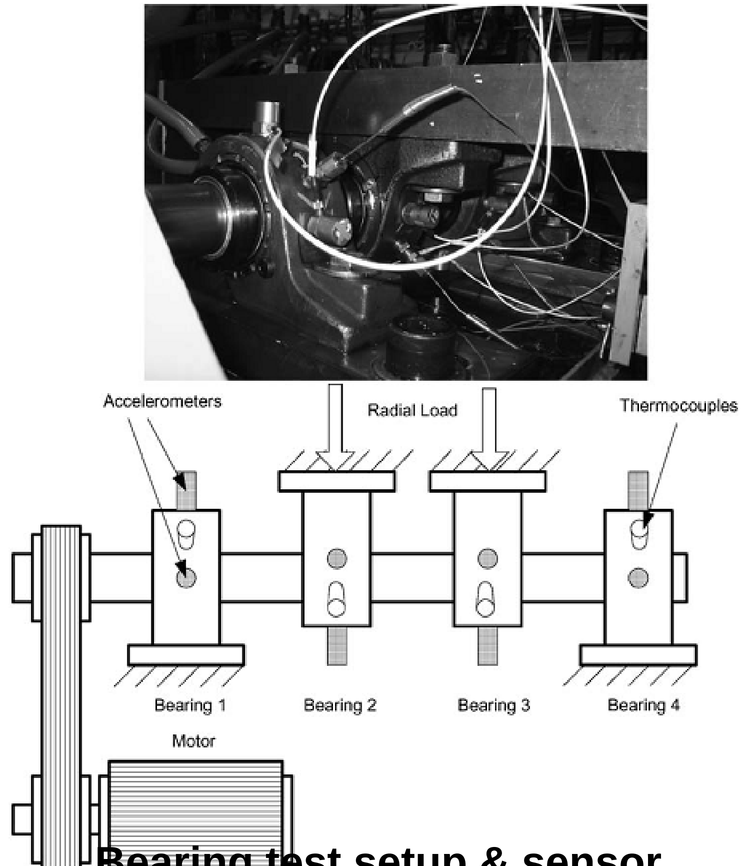
More tests are necessary (and underway) to improve results

NASA BEARING DATA SETS

Preliminary Results

Key Issues:

- **Natural defect propagation of machinery system**
- **Long-term progressive damage**
- **Signal de-noising & extraction of weak signature**
- **Performance assessment & complementary feature selection**
- **Prognosis at various defect stages**

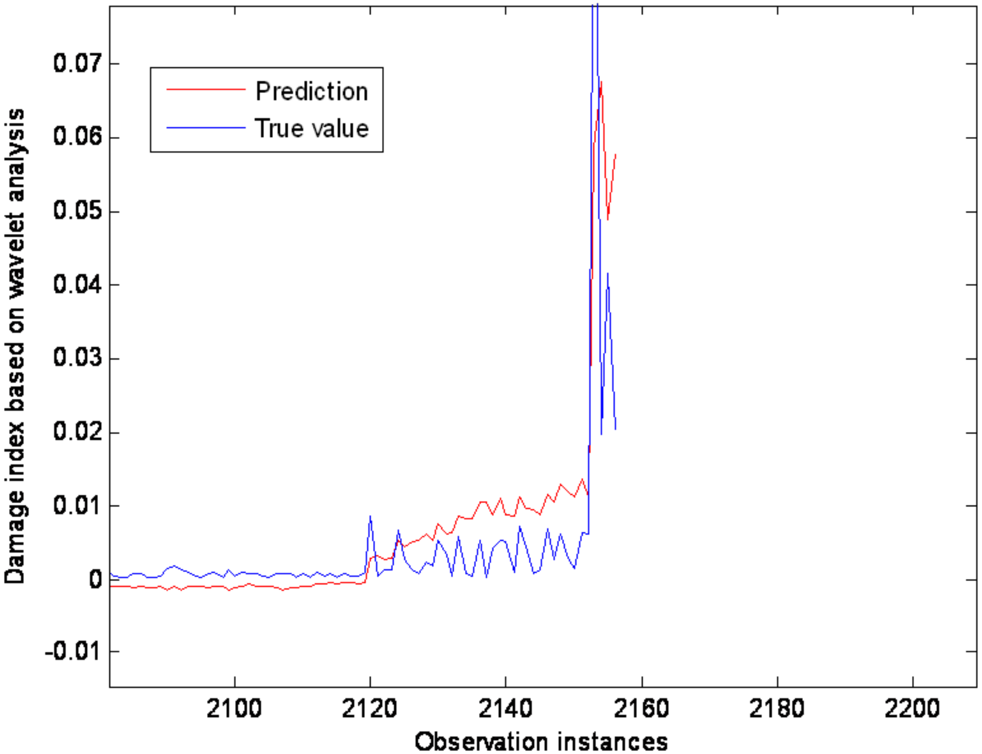


Bearing test setup & sensor placement illustration

Note: Figure and data sets from: Qiu et al. “Wavelet Filter-based Weak Signature Detection Method and its Application on Roller Bearing Prognostics”, Journal of Sound & Vibration, Vol. 289, 2006, pp 1066-1090.

Data sets Link: http://ti.arc.nasa.gov/projects/data_prognostics/

GAUSSIAN PROCESS PREDICTION

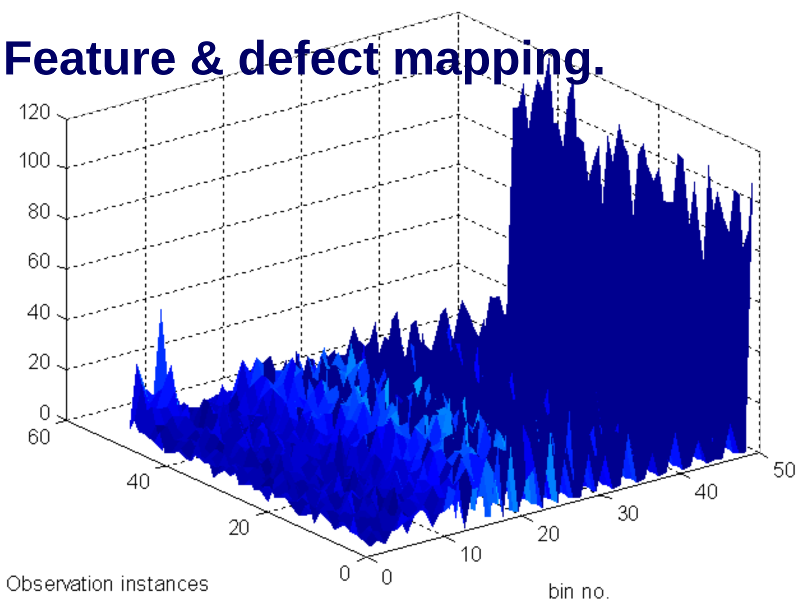


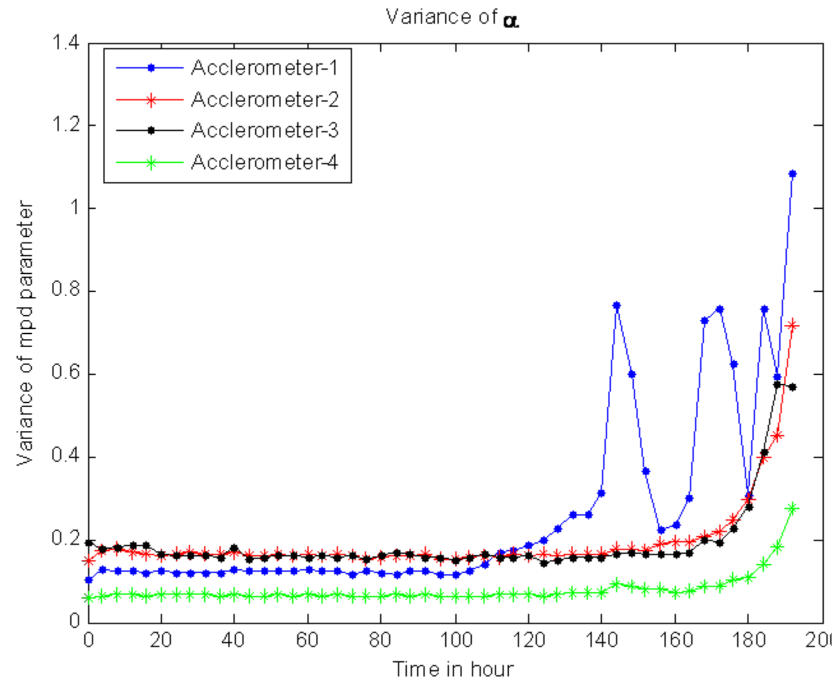
- **Gaussian process for online state estimation**
- **Based on wavelet features**
- **Good match between predicted state & experimental state during final phase of working life.**
- **Need better robust feature extraction algorithm**

MPD FEATURES STATISTICS

Preliminary results:

- **Feature selection: modeling an unknown function of a number of variables**
- **Combined time-frequency-domain feature analysis**
- **Feature & defect mapping.**

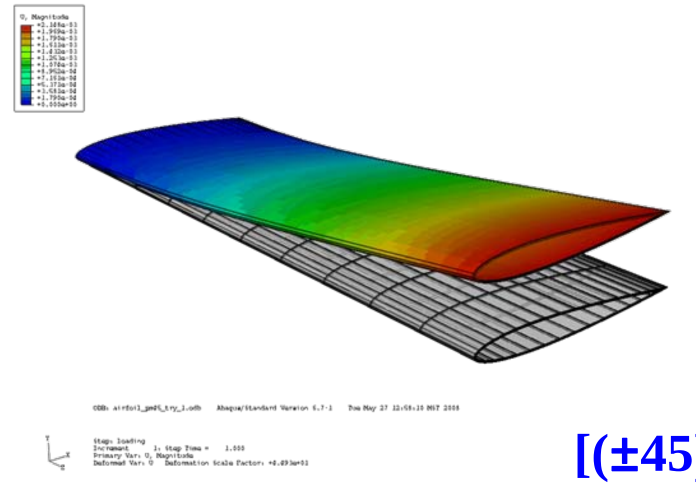




- **Redundant feature compression**
- **Comparisons of features between related sensors**
- **Feature trend for prognosis**

FUTURE WORK

- Multi-sensing composite fatigue and and bi-axial loading test (data for prognosis)
- Evaluate prognosis methodologies, such as Gaussian process, support vector regression, regression vector machine, particle filter, anomaly detection
- Evaluate current prognostic metrics & develop standardized novel metrics
- Compressive sensing algorithm & data compression
- Feature extraction, evaluation & complementary feature selection method
- Novel hybrid prognostic framework



$[(\pm 45)_2]_s$

Experimental Specimen